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ACTIVE NOISE CONTROL OF STAGELOADER NOISE IN LONGWALL MINING

Jeremy M. Slagley,[1,2] *Graduate Research Assistant*
Steven E. Guffey,[2] *Associate Professor*
[1] Air Force Institute of Technology
[2] Department of Industrial and Management Systems Engineering
West Virginia University, Morgantown, WV, USA

ABSTRACT

With the large scale mechanization inherent to the mining industry, noise-induced hearing loss remains a major concern. As part of on-going efforts to develop engineering controls to reduce noise levels in longwall mining, active noise control experiments were conducted above ground on a modified non-working stageloader. Recorded underground stageloader noise was broadcast into the above ground stageloader. The result was an average 7 dBA reduction when the active noise control was applied. These results suggest the possibility that active noise reduction can be a useful means to reduce stageloader noise if the control system can be made sufficiently rugged.

INTRODUCTION

Exposure to noise doses above established thresholds can cause irreparable sensori-neural damage to the auditory system. Substantial hearing loss can have strong adverse effects, including the insidious personal and social consequences associated with difficulties in communicating with others. (Royster and Royster, 2000) Although properly worn hearing protectors can sharply reduce the effects of unprotected noise exposure, it is commonplace to observe hearing loss in miners who have worked even a few years, perhaps because they have not always worn their plugs or muffs properly when exposed or because their hearing protection was less than effective under the conditions of mining. A National Institute for Occupational Safety and Health (NIOSH) study published in 1996 reported that hearing loss in miners was significantly worse than in the non-occupationally noise-exposed population despite decades of engineering interventions and use of hearing protection. By age 30, the range of loss of hearing in miners is equivalent to that of those who are 51 years old but have not been exposed to high levels of noise on the job. By 50 years of age, 90% of miners have hearing impairment.

Comparatively, the non-exposed people have a rate of only 50% with impaired hearing at 69 years old. (NIOSH, 1996).

Given the continued loss of hearing in miners despite the widespread use of hearing protection, it is important to reduce noise levels as much as possible. Since hearing loss increases sharply with level of noise, it is also important to reduce noise levels as much as is feasible even in cases where noise levels cannot be reduced to 85 dBA or less. For that reason, the Mine Safety and Health Administration (MSHA) historically has pressed for engineering changes that can produce even modest noise reductions though they may be difficult or costly.

Reducing noise is difficult in most industries, but the tight spaces and high mechanization of longwall coal mining makes noise reductions particularly challenging. MSHA has published numerous noise control guides and reports to assist mine operators in noise control efforts (Bartholomae and Burks, 1996, MSHA 1999), but much more progress is needed. Typical longwall coal mining crews are routinely exposed to more than 100% of the MSHA allowed noise dose.

One source of noise is the stageloader, which is the primary source of exposure for the headgate operator and a secondary noise source for the rest of the crew who must pass by the stageloader repeatedly. It is the object of this noise control investigation. For the study, noise characteristics from two stageloaders were investigated. Noise recorded from a stageloader was then used in tests of a non-working stageloader above ground.

BACKGROUND

As has been documented by MSHA inspectors in the noise dosimetry database (MSHA, 2004), the average noise dose for headgate operators working at the stageloader machine is 120.4% with a range of 18% to 373%. A better descriptor may be on the log-transformed data, as

exposure data frequently follow a lognormal distribution. The geometric mean is 100.2% and geometric standard deviation of 1.87. The actual noise level depends on many variables, including the length of the stageloader and where the operator spends most of his or her time, as will be discussed later.

There have been attempts to reduce the noise exposures to stageloader operators. Noise reduction can be accomplished, in general, by either blocking the path of the noise, reducing the sound power generated by the source, or by producing a noise equal to the source noise but 180 degrees out of phase. The latter is called "active noise cancellation" and the rest are variants of "passive controls." The noise path can be blocked by ear protection, such as ear muffs or plugs or by barriers or enclosures between the source and the operator.

Passive noise control

Ear muffs are almost universally worn by operators but are considered an inadequate solution for the reasons discussed earlier. Barriers, such as walls separating the stageloader from the operator could be extremely effective if the walls completely separated the machine from the operator. However, given the need for at least occasional access to the stageloader, the undesirability of impeding air movement and the frequent need to move the stageloader, complete walls are problematic at best. Partial shields could be of some value when the operator is very close to the ends, a possibility that is part of the on-going research by the authors.

Enclosing the entry and tail end of the stageloader while reducing noise emanating through the sides is a potentially highly effective means of reducing noise. To be effective, openings in the enclosure must be minimized and cannot face towards the operator. This would interfere with the operator's views of the machine. It may be possible to restore visual access using remote cameras inside the enclosures. However, the camera lens would be quickly coated with dust,

reducing the usefulness of the cameras, perhaps to the point that the operator would open the enclosure to improve visual access.

Reducing the sound power always has the potential to dramatically reduce noise exposures but often involves severe tradeoffs. For example, the sound power from impacts of the coal on the stageloader could be reduced by cutting holes in the sides. However, this would allow noise now transmitted down the interior of the stageloader to issue from the sides, possibly increasing exposures. Likewise, noise due to the chains could be reduced by coating them with an absorbent urethane.

One unpublished study at NIOSH's Pittsburgh Research Laboratory investigated coating the flights on the chain conveyor of a continuous miner with a urethane material. The study detected good noise reduction and durability issues are improving to increase practicality. In another unpublished study, researchers applied damping material to the exterior of a stageloader. Noise levels in the immediate area of the application were reduced, but noise at other locations along the stageloader increased. (Metatic and Reeves, 2003) Continuing the application along the stageloader would conceivably send the noise out the tail end towards the belt entry. The stageloader is essentially a duct through which the coal is loaded out onto the belt. There is usually an air gap above the coal surface, at least up through the gooseneck. This air gap in a duct would be the medium through which the interior noise could be channeled when exterior passive noise controls are applied.

This discussion is not intended as a dismissal of the potential benefits of re-engineering for noise reduction or of enclosures or partial barriers. It is conceivable that a feasible solution will some day emerge from these approaches. However, the progress to date has been modest and hard-won. Furthermore, most passive methods are typically most effective with high frequency noise (e.g., greater than 500 Hz) and least effective with lower frequency noise. As is discussed

in later sections, noise recorded from two operating stageloaders by the authors was dominated by low-frequency noise.

Active noise control

The remaining method, active noise cancellation, has many practical difficulties and limitations of its own, but it does have the virtue of utility for low frequency noise. For that reason, the authors explored the potential effectiveness of active noise cancellation to reduce noise emanating from a stageloader. If ANC could be made practical in the mining environment, it would be well-suited to reducing lower frequency noise in ducts. Combining the lower frequency control of ANC with higher frequency control provided by traditional passive controls may be a viable option for engineering controls in longwall mining.

Active noise control (ANC) is a technique of noise reduction by creating a 180° out-of-phase noise signal to cancel the noise source. A diagram of a feedforward ANC system in a duct is in Figure 1. A reference microphone is used to sense the signal of noise traveling along the duct. The signal is analyzed at the controller using a fast Fourier transformation, and an out-of-phase sound is broadcast into the duct via a control speaker. An error microphone then picks up the residual noise in the duct and an algorithm in the controller seeks to minimize the noise detected at the error microphone.

Although ANC has been applied in 3-dimensional spaces successfully (Gulyas et al, 2002), the simplest application of ANC methods are in enclosed linear spaces, such as ducts, where the noise source can produce standing waves. The standing waves are essentially 1-dimensional problems and can be attacked easily (Bies and Hansen, 2003). The highest frequency of standing wave to set up will be linked to the largest cross-sectional dimension of the duct. For instance, if the duct is 11 cm by 12 cm, the widest cross-sectional dimension is the diagonal 16.3 cm. The highest frequency that can be expected to set up a standing wave is the wavelength divided by

four (λ/4). So the shortest wavelength would be (4 x 16.3 cm=65.1 cm). Given the speed of sound in air of 344 m/s, the highest frequency would be (344 m/s / 0.651 m = 528.3 Hz).

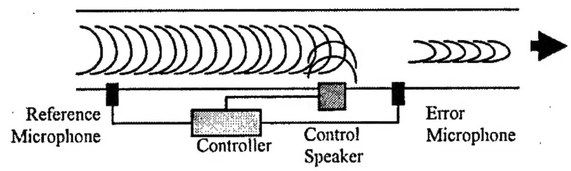

Figure 1. Schematic of feedforward active noise control system in a duct.

The height above coal in an operating stageloader typically varies erratically and unevenly from 0 to 30 cm before the end of the gooseneck. The width of the two operating stageloaders and the test stageloader were all about 1.2 m. Based on those dimensions, the maximum frequency for effective noise cancellation would be about 70 Hz, which is of little utility. As is discussed in following sections, the authors propose to divide the width of stageloaders into distinct channels using 13.5 cm high steel vertical dividers.

The study was divided into two phases. First underground noise surveys were carried out at two different mines. The second phase of the study was the ANC experiments on the above ground non-operational stageloader.

METHODS AND APPARATUS

The authors first investigated noise levels at two mines to characterize the noise levels, dose to the operators, and operating parameters of two different stageloaders. Then recorded stageloader noise was used in active noise tests of a non-working above ground stageloader.

Underground stageloader noise surveys

Sound levels and noise dose data were recorded in 10 surveys at two different mines. A Quest 2900 Octave Band Analyzer was used for sound levels and Quest Q-300 Noise Dosimeters were used for noise dose data. The Octave Band Analyzer was a Type II device calibrated

before and after each survey with a Quest QC-10 Calibrator. (Quest Technologies, Inc., Oconomowoc, WI) The noise dosimeters were single microphone 3-channel devices that were capable of applying three different criteria level/threshold level/exchange rate schemes to logged data. The dosimeters were set to log the average level minute-by-minute. The dosimeter schemes are listed in Table 1.

Parameter	Dosimeter 1	Dosimeter 2	Dosimeter 3
Weighting	A	A	A
Threshold Level	90 dB	80 dB	off
Criterion Level	90 dB	90 dB	85 dB
Exchange Rate	5 dB	5 dB	3 dB
Response	Slow	Slow	Slow
Upper Limit	140 dB	140 dB	140 dB
Designation	MSHA permissible exposure limit	MSHA Action Level	Wide range

Table 1. Noise dosimeter settings.

For this study, the authors investigated exposures at two very different stageloaders. The first was a Joy stageloader and crusher assembly used for a 2.4 m-seam in the mid-Atlantic region (Pittsburgh seam). It was 41.8 m long and 1.22 m wide running at 126 m/min. The second was a DBT America stageloader and crusher assembly used for a 2.0 m-seam in the Mid-Atlantic region. It was 21.3 m long and 1.20 m wide running at 128 m/min. This paper refers to the longer Joy model as the "long" stageloader, and the shorter DBT stageloader as the "short" one.

Active Noise Cancellation

Recorded underground mine noise was reproduced into an 8.5 m (28 ft) section of stageloader. The stageloader machine is a duct with an air space that varies, but under normal operation has been described by operators and observed by the authors as roughly 15.2 cm (6 inches) in height across the width of the stageloader. The short stageloader width was

approximately 1.2 m. This means that the highest frequency controllable by ANC would be (344 m/s)/(4 x 1.21 m) = 71 Hz, which is much too low to be useful. Hence, for ANC to be used effectively, it is necessary to reduce the apparent width of the stageloader. A typical technique to reduce a dimension in a duct for ANC application is to insert splitting vanes down the length of the duct so that the duct is split into several smaller channels.

In order to limit the airspace above the coal inside the stageloader so that higher frequencies could be controlled, a 13.5 cm high vane was added down the length of the section. Also, a shelf containing coal was constructed inside the stageloader to recreate typical physical dimensions during use. The resulting area of the opening was 17 cm wide by 13.5 cm high. (Figure 2.) The 17 cm wide channel would theoretically allow standing waves up to (344 m/s)/(4*0.23 m) = 377 Hz.

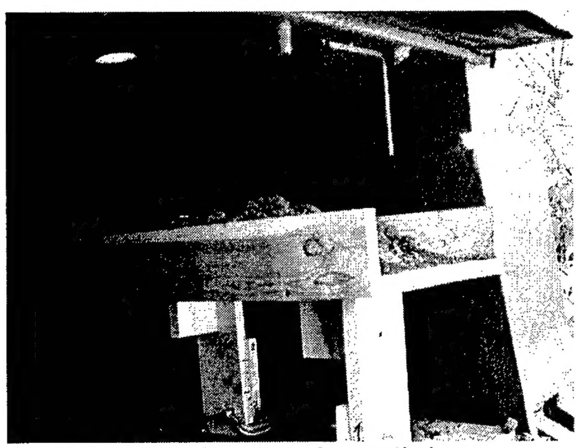

Figure 2. Crusher end of stageloader section showing splitting vane and shelf loaded with coal.

Three parameters were selected for investigation. First, shelf height, which dictates the cross sectional area and the amount of noise "leaking" into and out of the channel was set at either flush with the vane (13.5 cm x 17 cm cross section), or sloped. For the sloped trials, the section of stageloader directly after the crusher was sloped from a height of 20.5 cm to 13.5 cm over a distance of 2 m to better resemble the airspace dimensions during use.

The second parameter was the distance between reference microphones and control speakers. The longer the distance, presumably the better the standing wave and the more time the system has to process the reference signal and counter it.

The third parameter was the number of references microphones, controls speakers, and error microphones used. Some initial tests seemed to indicate that having two independent systems operating on the same noise increased the frequency range that could be controlled and therefore reduced the overall noise level further. Therefore two systems were evaluated, one using a 2x2x2 (2 reference microphones, 2 control speakers, and 2 error microphones) feedforward ANC system, and the other a 1x1x1 system.

The recorded stageloader noise was random and broadband in frequency content. The EZ-ANC II Active Noise Controller (Causal Systems, Inc., Adelaide, Australia) was used to analyze the recorded noise and generate the countering signals. Coherence of the reference and error microphones was satisfactory by comparing the frequency response of the microphones to the same signal. The system was also found to be sufficiently causal. Causality refers to the fact that the reference microphones picked up the noise of concern rather than the control speaker noise. This was attained by inserting the reference microphones into 1.22 m, model X5305 microporous plastic tubes (Porex Corp., Fairburn, GA) so that they were directional toward the source noise.

The reference and error microphones were placed directly in the channel and isolated from vibration with 4 cm thick foam. The control speakers were placed outside of the channel with the speaker face centered on an opening into the channel. A separate microphone located with the error microphones fed the final noise to an OR-38 Real-Time Analyzer (OROS, Inc., Dulles, VA) for instantaneous analysis. The relative position of the speakers and microphones are shown in Figure 3.

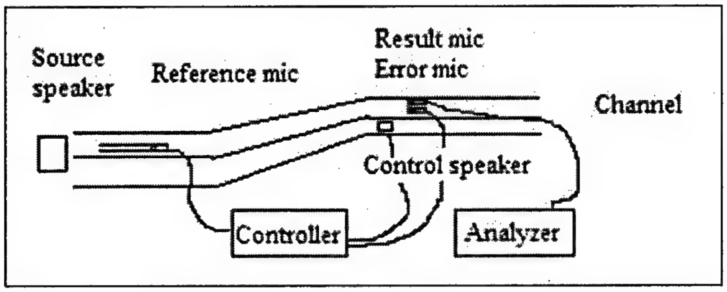

Figure 3. ANC test apparatus

All microphones were calibrated with a QC-20 Calibrator (Quest Technologies, Oconomowoc, WI) before and after the trials. Background noise was monitored during each trial to ensure it was at least 10 dB below the reduced levels in the frequency bands of concern.

The ANC device was allowed to stabilize for at least 1 minute before establishing weighting values for the frequency spectrum based on a random noise model. The OR-38 then recorded a 30 second sample and the average 1/n octave sound levels were recorded with ANC on and off.

A factorial experiment was conceived with two shelf heights, H, (flush with coal 17 cm x 13.5 cm or sloped from 17 cm x 20.5), two systems, S, (single or dual), and three microphone distances, D, (4.67 m, 6.24 m, and 8.33 m). Two repetitions were performed and all trials were randomized except the shelf height, which was difficult to adjust. All 12 trials were performed on one shelf height, then the shelf height was adjusted and the next 12 performed.

RESULTS

Underground stageloader noise surveys

The operator of the long stageloader could have been exposed to anywhere from 84 dBA to 106 dBA (Figure 4), depending on where he spent most of his time. Fortunately, he spent nearly

all of his time at the control panel seat and was therefore exposed to the relatively low levels at that location, giving him a dose of 44%. His minute by minute exposures are shown in Figure 5.

The operator of the second stageloader could have been exposed to anywhere from 90 to 98 dBA (Figure 6). Because this stageloader was shorter, no location along its length was far enough from the main noise sources of the crusher, headgate drive, and tail drive, to be as low as the long stageloader. This stageloader had no seat and the operator spent much of his time at the noisy control panel/crusher/headgate drive area next to the T-junction. The stageloader machine is the primary noise source for the operator's exposure. His minute by minute exposures are shown in Figure 7.

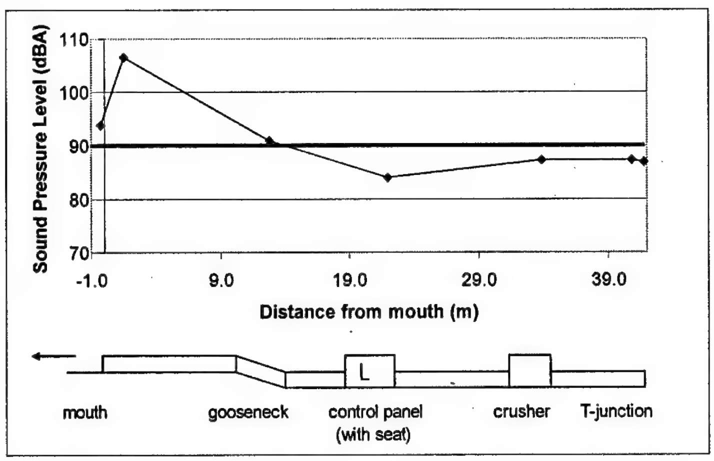

Figure 4. Noise levels (dBA) along the long stageloader

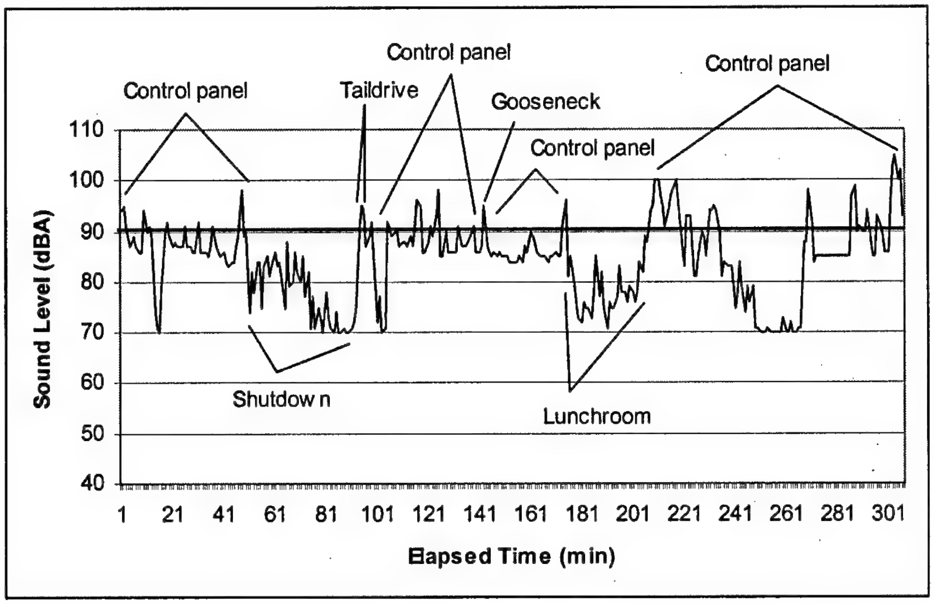

Figure 5. Minute-by-minute noise level exposure to long stageloader operator.

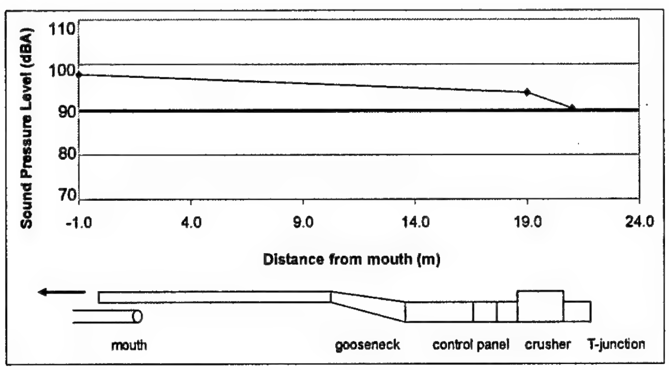

Figure 6. Noise levels (dBA) along the short stageloader

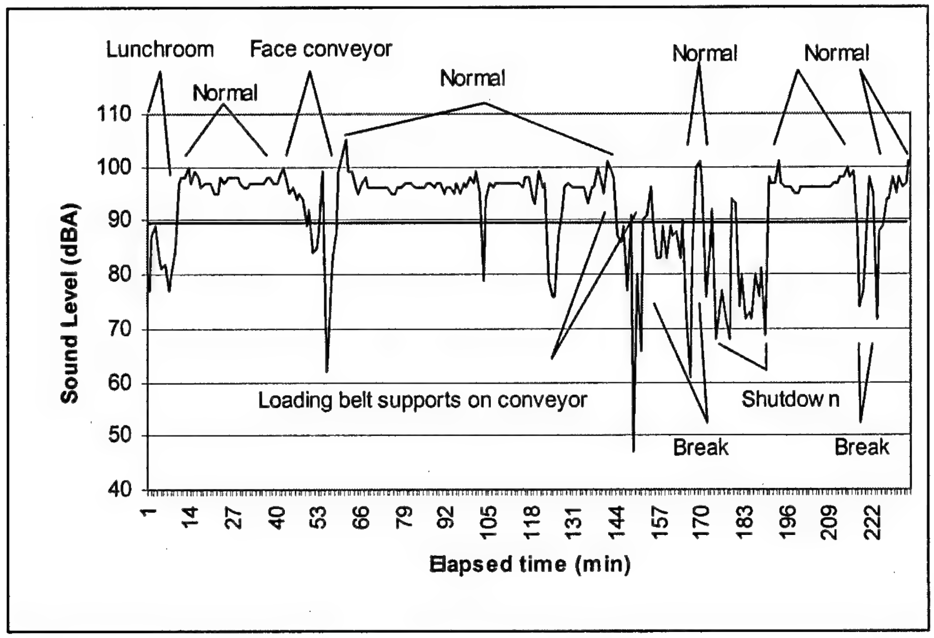

Figure 7. Minute-by-minute noise level exposure to short stageloader operator.

MSHA noise dosimetry data from 2000-2004 for the headgate operators at the two mines are listed in Table 2. A two-sample, two tail t-test assuming unequal variances performed on the log-transformed data indicates that these two groups are significantly different (p=0.0137).

Occupation	n	Geometric Mean Dose	Geometric Standard Deviation
Headgate, short SL	5	103.1%	1.47
Headgate, long SL	4	23.3%	1.79

Table 2. Average 8-hour noise dose for headgate operators at long and short machines.

For this reason, the short stageloader was selected for noise control investigation. The noise frequency spectra for those areas where the operator spent most of his time are presented in Figure 8.

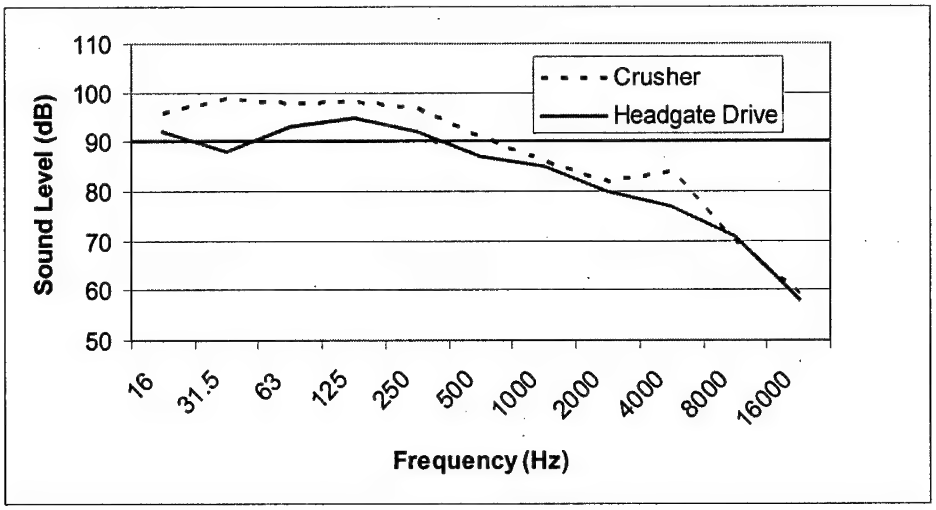

Figure 8. Short stageloader frequency spectrum for crusher and headgate drive locations

A significant amount of sound energy was present below 1000 Hz. Observing the higher of the two, the crusher noise, it is apparent that the noise in the octave bands below 1000Hz contribute 92 dBA to the overall 94 dBA average value. Indeed, a 10 dB reduction at each octave band below 1000 Hz would reduce the overall level to 90 dBA.

Active Noise Control

All ANC results were analyzed using the statistical analysis software JMP (SAS Institute, Inc., Carey, NC). An analysis of variance (ANOVA) was run on the additive linear model of the three independent variables and their effect on the noise reduction (NR) of the recorded noise (Table 3).

Model: $NR_{ijkl} = \mu + H_i + S_j + D_k + \varepsilon_{ijkl}$					
Source	Degrees of Freedom	Sums of Squares	Mean Squares	F-statistic	P-value
Model	3	30.70	10.23	3.08	0.0509
Shelf Height (H)	1	0.30	0.30	0.09	0.7655
System (S)	1	2.10	2.10	0.63	0.4359
Microphone Distance (D)	1	28.30	28.30	8.52	0.0085
Error	20	66.44	3.32		
Total	23	97.15			

Table 3. ANOVA of noise reduction model with all variables

The overall model was very nearly significant (p=0.0509). Both shelf height and dual vs. single system were found to be not significant (p=0.7655 and p=0.4359, respectively), so they were removed from the model. Microphone distance was significant at p=0.0085. When the noise reduction was modeled on microphone distance alone, the results were significant (p=0.0065) and are given in Table 4. The simplified model was based on microphone distance alone:

Model: $NR_{ij} = \mu + D_i + \varepsilon_{ij}$					
Source	Degrees of Freedom	Sums of Squares	Mean Squares	F-statistic	P-value
Model (Microphone Distance, D)	1	28.30	228.30	9.04	0.0065
Error	22	68.85	3.13		
Total	23	97.15			

Table 4. ANOVA of linear model based on microphone position only

Interaction among the variables was also tested, but the most significant model remained the linear model based on microphone distance alone. The reduction by microphone distance is given in Table 5 in A-weighted and unweighted decibels.

	Unweighted (Linear)	A-weighted
Microphone Distance	Average ± standard deviation (dB)	Average ± standard deviation (dBA)
4.67 m	4.3 ± 1.5	4.2 ± 1.1
6.24 m	4.8 ± 1.6	5.4 ± 1.3
8.33 m	6.9 ± 2.2	7.0 ± 2.2
Overall	5.3 ± 2.1	5.5 ± 1.9

Table 5. Noise reduction by microphone distances

A typical unweighted frequency spectrum for the recorded stageloader noise before and after ANC is shown in Figure 9. The noise was largely low frequency, so the ANC system focused on that portion of the noise.

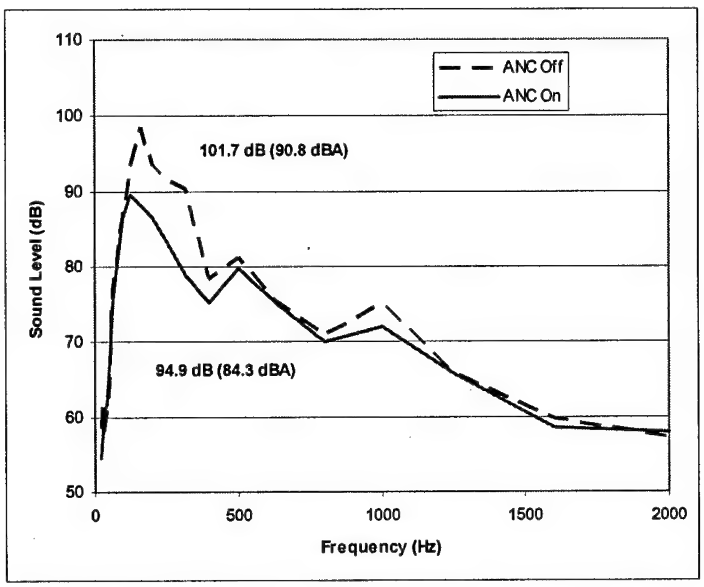

Figure 9. Typical frequency spectrum of stageloader noise before and after ANC

DISCUSSION

The potential benefit to the stageloader operator is intriguing yet constrained by the environment. Given the average reduction by frequency for the best performing microphone distance (8.33 m) and the crusher noise of the short stageloader, the resultant overall noise level would be 91 dBA. (Table 6.) While this level would not be at or below 90 dBA, the operator

could remain in the area for 418 minutes (roughly 7 hours) with the crusher operating continuously before reaching 100% dose. Expected dose for a continuous 8 hour exposure would be 115%, below the 132% citation threshold used by MSHA. (MSHA, 2001)

Average Reduction at Microphone Distance 8.33 m	Resultant Stageloader Crusher Noise Level (dB)	A-weighted Result (dBA)
0	99.0	59.6
0	98.0	71.8
3	95.2	79.1
10.2	86.8	78.2
3	88.0	84.8
0	86.0	86.0
0	82.0	83.2
0	84.0	85.0
0	70.0	68.9
	Overall	91

Table 6. Potential reduction of short stageloader noise by ANC using best microphone position

The potential success is limited by the fact that the noise reduction would occur downstream of the microphone, so that the miner would only benefit if he were standing at least 9 m downstream of the crusher. However, using ANC technology in conjunction with passive controls may be promising. If passive controls reduce the noise in the walkway around the crusher and control panel, but channel the noise down the airspace above the coal in the stageloader, then the ANC system could reduce the channeled noise. This combination of controls may be able to effectively reduce noise levels at all work areas for the headgate operator.

CONCLUSION

Active Noise Control technology has long been used for noise in duct problems. It has been successfully demonstrated here in an application on the stageloader for longwall mining. ANC

could potentially garner a 7 dBA reduction in stageloader noise. Its application could be relevant when combined with traditional passive noise control techniques to reduce headgate operator noise dose. Further research is ongoing to resolve practical difficulties in implementation, including mounting techniques to protect the microphones and speakers, robustness and simplicity of system operation, and intrinsic safety issues. The microphones and control speaker would be mounted in protective steel boxes above the stageloader with a membrane, air curtain, or some other method to keep the system clean of dust and moisture while still allowing sufficient air pressure fluctuation to respond properly. The boxes would have to be mounted in a section of the stageloader that was not prone to hitting the roof when uneven floor causes the stageloader to tilt. The ANC control system would be mounted in an explosion-proof box with electrical barriers applied to the input and output lines in order to comply with intrinsic safety standards. Lastly, the control system would have to be tested for vibration tolerance and insulated accordingly. Figure 10 displays the mounting concept for the stageloader.

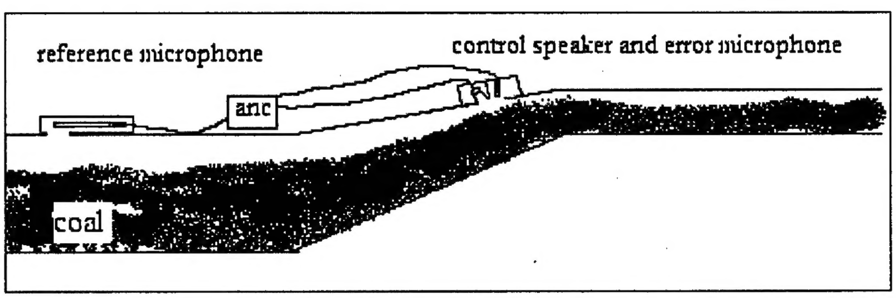

Figure 10. Mounting concept for ANC on a stageloader

It should be reiterated that even simpler controls, like relocating the headgate operator to quiet areas, would be more effective for noise dose reduction. The headgate operator at the long stageloader using the provided seat was never overexposed to noise.

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